Description of differences between the sound of trumpets, played by a musician or simulated by physical modelling

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This paper addresses the comparison of simulated sounds of trumpets to real sounds played by a musician. Three different trumpets, obtained by geometrical variations of the leadpipe, are considered. After a measurement of the input impedance of the trumpets, they are first simulated using the harmonic balance technique, and second played by a musician. Different playing conditions are considered, either for the simulations (virtual musician defined by the control parameters of the simulation) or for the "real" musician (playing at different dynamics). The two populations of sounds produced are characterized by their spectrum in permanent regime. Results show that for sounds with a steady dynamics, there is a disagreement between the simulations and the musician on the differences between the instruments. For sounds with an increasing dynamics (crescendo), a modeling of the effect of the instrument with analysis of variance shows a good agreement between the simulation and the musician, in particular for the spectral centroid of the sounds. This interesting result opens the door to virtual acoustics for instrument making.

1 Introduction

The development of physical models of musical instruments is particularly interesting to understand their functioning and to justify their design. They could also be used to propose design modifications to the instrument maker, in order to improve the quality according to the wish of the musicians [1].

In this context, simulations by physical modeling are particularly interesting [2] but still in their beginning phase concerning instruments making. In this paper, we are interested in the ability of simulations by physical modeling to be in agreement with sounds played by a musician. Our study focuses on a particular brass instrument: the trumpet.

In a previous paper [3], we described a special parameterized leadpipe, a device that allows ones to finely control the differences between instruments. For sounds played with an artificial mouth with an increasing dynamic (crescendo), we showed that the evolution of the spectral centroid is a typical feature of the used leadpipe. In another paper [4], we showed that sound simulations with the harmonic balance technique, based on a measurement of the input impedance, are able to generate sounds which are also typical of the leadpipe used. The control parameters of the simulation (the "virtual musician") have a realistic influence on the sound (i.e. in agreement with the physics of the instrument) [5].

In [6], we studied the influence of the leadpipe on the sound of the trumpet in permanent regime. We showed that the effect of the leadpipe on the playing frequency, for simulated notes with a steady dynamics, is in agreement with the results obtained with a musician. Concerning the timbre of the sounds, we showed that there is no significant difference between the spectral centroid of the sounds, neither for the simulations nor for the sounds played by a musician.

In this paper, we propose to study the differences between sounds simulated by physical modeling and played by a musician. For this, we used 3 different trumpet leadpipes and generated sound either by simulations, or with a musician. Section 2 presents the experimental device, the principles of the sounds simulation with the harmonic balance technique, and describes the recording of the sounds with a musician. Section 3 presents the results concerning the comparison of the simulated sounds to the "real" sounds.

2 Materials and methods

2.1 The parameterized leadpipe

The leadpipe, located between the mouthpiece and the tuning slide of the trumpet, is a roughly conical part which has a great influence on the intonation and the timbre of the instrument. From the measurements of the internal form of existing leadpipes (measured with calipers), a parameterized leadpipe, made of 4 different interchangeable parts, each conical and parameterized by the radii r_1, r_2, r_3, r_4 (figure 1), was designed.

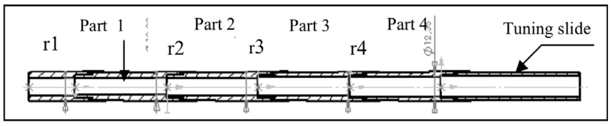

Figure 1: design of the parameterized leadpipe

Several parts 1-2-3-4, with various values for the radii r_1, r_2, r_3, r_4, have been manufactured with a numerically controlled turning machine. The proposed values of r_1, r_2, r_3, r_4 correspond roughly to dimensions of marketed leadpipes, and the assembling of the parts allows the generation of various inner profile (many hundreds). A coding of each leadpipe, made of 4 letters (one letter for each part, the letter corresponding to a given dimension of the radius), has been defined in order to distinguish the leadpipes. So, using the same trumpet (*Bach* model *Vernon*, bell 43) and the parameterized leadpipe (figure 1), three leadpipes, whose characteristics are presented in table 1, were studied.

Table 1: description of the dimensions (in mm) of the three leadpipes of the study

	Part 1		**Part 2**		**Part 3**		**Part 4**	
	r_1	r_2	r_2	r_3	r_3	r_4	r_4	r_5
AAAE	4.64	4.64	4.64	4.64	4.64	4.64	4.64	5.825
DKOS	4.64	5.45	5.45	5.5	5.5	6	6	5.825
CHMQ	4.64	5	5	5.5	5.5	5.7	5.7	5.825

Using the same mouthpiece (Yamaha 15B4), and the same remaining part of the trumpet (Bach, bell 43, model *Vernon*), the input impedance Z of the 3 trumpets were measured with the BIAS device [7] at ITEMM (Institut Technologique Européen des Métiers de la Musique, Le Mans, France). This measurement, characteristic of the instrument, is the input of the sounds simulations.

For the choice of the inner shape geometry of the leadpipe, two leadpipes (DKOS and CHMQ) were chosen very similar (the only difference, greyed in table 1, concern the radii r_2 and r_4, with some hundredth of mm). Subjective blind tests showed that musicians were definitely not able to recognize these two trumpets. The third leadpipe, AAAE, presents significant variation in the inner shape, and also in the input impedance. Musicians were able to blind recognize this leadpipe, mainly for intonation but also for timber reasons.

2.2 Simulation with the harmonic balance technique

Basically the harmonic balance technique is a numerical method computing converging periodic solutions *p(t)* of a system while taking a given finite number N of harmonics into account in a truncated Fourier serie Eq.(1):

$$p(t) = C_o + \sum_{n=1}^{N} A_n.\cos(2\pi n F_o t + \varphi_n) \quad (1)$$

The unknowns of the problem are the harmonic amplitudes A_n (C_o and φ_n) and the playing frequency F_o (details of the technique in [8]).

The physical model is based on the 3 following equations (Eq. (2-3-4)), which involve the three periodic variables; the opening height *H(t)* between the two lips of the player, the volume flow *v(t)* at the entrance to the mouthpiece, and *p(t)* the pressure in the mouthpiece:

$$v(t)=b.H(t)\sqrt{\frac{2(P_m-p(t))}{\rho}} \quad (2)$$

$$\frac{d^2}{dt^2}H(t)+\frac{\omega_L}{Q_L}\frac{d}{dt}H(t)+\omega_L{}^2H(t)=\frac{P_m-p(t)}{\mu_L} \quad (3)$$

$$P(j\omega) = Z(j\omega).V(j\omega) \quad (4)$$

A numerical solution *p(t)* of this system of equations can be computed, according to the control parameters of the simulation: a solution *p(t)* (Eq. (1)), given by C_o, A_n and φ_n, satisfying Eq. (2, 3 and 4), can be defined if the system converges.

In order to generate various sounds with the same instrument, it is necessary to define several “virtual musicians”, given by their “control parameters”. Three parameters have been chosen to represent the virtual musician: the input pressure in the mouth P_m, the resonance frequency of the lips f_L, the inverse of the mass per area of the lips $\nu_L = 1/\mu_L$. The ranges of variation of these parameters are given in table 2. These ranges have been defined after a systematic exploration of the “parameter space”, and correspond to values of the parameters leading, for at least one trumpet, to the convergence of the simulation. Given the ranges of the parameters, the maximum number of possible sounds generated per trumpet is 8×40×6 = 1920.

The values of the other lips parameters (fixed for all the simulations) have been adapted from the study of Cullen et al. [9]. The different values of the control parameters and the lips parameters are summarized in table 2.

Table 2: parameters of the simulations

Control parameters		
Definition	*Notation*	*Value*
Pressure in the mouth	*Pm* (Pa)	8000 to 22000 (step of 2000)
Resonance frequency of the lips	$f_L = \omega_L/2\pi$ (Hz)	400 to 439 (step of 1Hz)
Inverse of the mass per area of the lips	$\nu_L = 1/\mu_L$ (m^2kg^{-1})	-0.5 to -3 (step of -0,5)
Width of the lips	b (mm)	10
Rest value of the opening height	H_o (mm)	0.05
Quality factor of the resonance	Q_L	5

The outputs of the simulations used to characterize the sounds are only the playing frequency F_0 and the magnitude A_n of the N first harmonics of the note (the phase φ_n was not considered). Each trumpet is then represented by a $p\times(N+1)$ matrix, with p the number of sounds generated with this trumpet, and $N+1$ the number of variables describing the sound (F_0 and N amplitudes A_n, $n = 1$ to N). For the three trumpets, the note simulated corresponds to the fourth partial of the instrument (Bb4; F = 466.16Hz). 6 harmonics (N = 6) of the notes have been considered for the simulation.

It has to be noticed that the approached solutions *p(t)* coming from the elementary model are corresponding to the acoustic pressure inside the instrument mouthpiece. In order to compare to the real sound, it is necessary to obtain the acoustic pressure outside the resonator, at the level of the bell. For this, according to the works of Benade [10], we used the spectrum transformation function. The resonator is considered in this case as a high pass filter, the filter’s envelope corresponding to the transfer function of the instrument. We considered a filter corresponding to a “theoretical” trumpet, and applied the same filter to the 3 instruments. This is of course an approximation, but it is likely that the differences generated on the external sounds are negligible. For each instrument, the series of external sounds was computed by multiplying directly the magnitude of the harmonics by the filter’s coefficients. Each instrument is than represented by a matrix whose rows correspond to different sounds, and 7 columns corresponding to the variables (F_0 playing frequency and $N=6$ amplitudes a_n, $n = 1$ to 6).

2.3 Recording of the sounds with a musician

For the 3 leadpipes, the same note (Bb4) was recorded with the same musician. All the recordings (sampling frequency 44100Hz, 16 bits) were made in the same room with a *Shure* SM 58 microphone. The microphone was placed in the axis of the bell (distance = 10 cm) and connected to the preamplifier and a *Digigram* Vx pocket

V2 soundcard. The position of the tuning slide was the same for all the leadpipes. In order to limit as much as possible the variability inherent to the musician, he was asked to play the note in the easiest and more natural way (without trying to adjust the height or the timbre of the tones). The duration of the sounds was about 3 seconds, two series of notes being recorded:

- Series 1: with a steady dynamic (*forte*). 10 repetitions of the same note,
- Series 2: with an increasing dynamic (crescendo). 20 repetitions of the note, increasing progressively from *pp* to *ff*.

The sounds were next windowed to suppress the transient part of the signal. With the remaining part of the signal (considered as the permanent regime), the playing frequency and the magnitude am_i of the 20 first harmonics were estimated with the synchronous detection method. For every sound, the spectral centroid was computed (with $N = 6$ for the simulations, and $N = 20$ for the musician) (Eq. 5).

$$Sc = \sum_{k=1}^{N} k.a_k \Bigg/ \sum_{k=1}^{N} a_k \tag{5}$$

The spectral irregularity (a measurement of the jaggedness of the spectral envelope) was computed according to Eq. (6).

$$IRR = \sum_{k=2}^{N-1} \left| a_k - \frac{a_{k-1} + a_k + a_{k+1}}{3} \right| \tag{6}$$

3 Results and discussion

3.1 Series of notes with a steady dynamics

In order to compare the spectrum simulated with each trumpet, we have to select simulations with the same virtual musician (same control parameters of the simulation). We considered the sounds corresponding to a given value of the pressure Pm (Pm = 16 000 Pa), 4 values of f_L (400; 404; 408; 412Hz) and 3 values of ν_L (-3; -2.5; -2). For each instrument, only 11 sounds were generated (convergence of the simulation for 11 sounds among 3*4 = 12 cases). The average external spectrum of each trumpet, obtained by averaging the amplitude of the harmonics of the 11 sounds, is given figure 2. Figure 2 shows that:

- For almost all the harmonics, the amplitude of the trumpet AAAE is greater than those of CHMQ and DKOS.
- For all the harmonics, the amplitude of the trumpet CHMQ is greater than those of DKOS.
- AAAE is rather different than CHMQ and DKOS, DKOS and CHMQ are more similar.

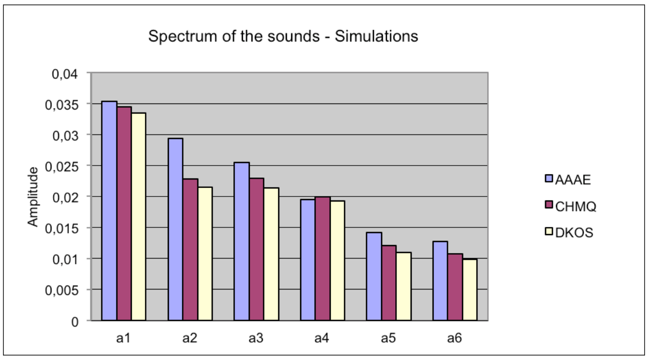

Figure 2: average external spectrum of the 3 trumpets (Simulations) – pressure Pm = 16 000 Pa.

This last conclusion is in agreement with the differences in the geometry of the leadpipes: very similar leadpipes from a geometrical point of view lead to very similar simulated sounds from an acoustical point of view.

Nevertheless, the average spectrum of the simulated sounds is different of the typical spectrum of a trumpet, played by a musician: it corresponds to a real modern trumpet played pianissimo (decreasing amplitude of the harmonics). Further studies are needed to explain why the physical model is unable to produce a typical spectrum of a trumpet (non linear effects, frequency limitation in the measurement of Z,…).

The amplitude of the harmonics for sounds played by the musician is given figure 3.

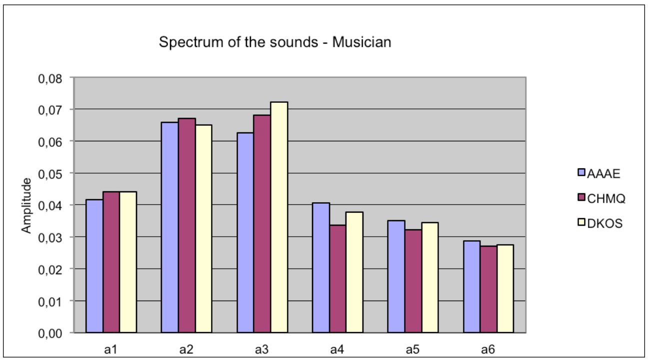

Figure 3: average external spectrum of the 3 trumpets (Musician)

Figure 2 and 3 show first that the spectrum of the simulated sounds is very different of the spectrum of the real sounds: the spectrum of the simulated sounds is not typical of the spectrum of a played trumpet (harmonic 2 and 3 are usually more powerful than harmonic 1).

Second, we notice that the differences between the trumpets do not seem to be in agreement, for the simulations and the “musician”. To visualize clearly the differences, we computed, for each configuration (simulation or musician), the standard scores of the amplitudes (subtract the average value and divide by the standard deviation). The standard scores of the amplitudes are given figure 4 and 5.

We see clearly on figure 4 and 5 that the differences between the trumpets are not in agreement, for the simulation and for the musician: the patterns of the relative spectrum are different.

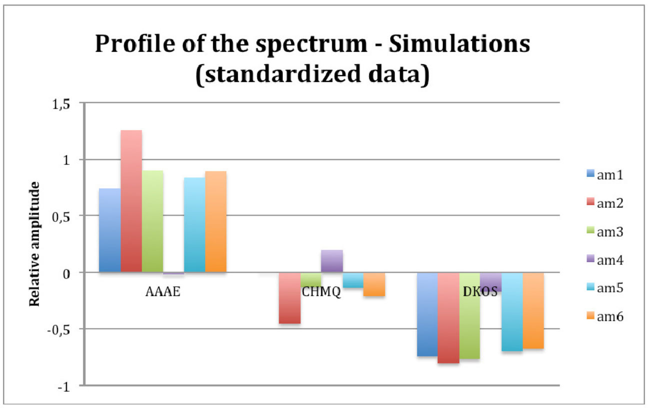

Figure 4: profile of the external spectrum of the 3 trumpets for the simulations – standardized data.

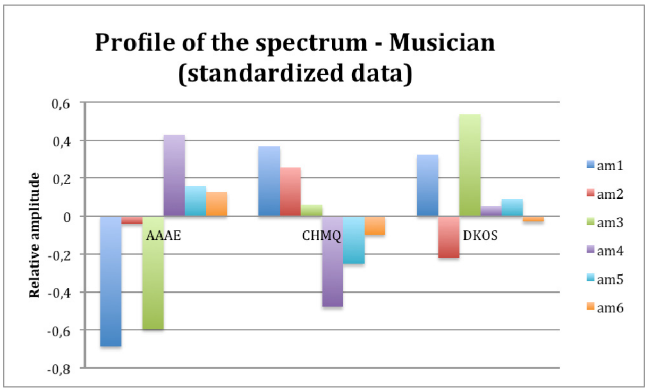

Figure 5: profile of the external spectrum of the 3 trumpets for the musician – standardized data.

For the simulation (figure 4), AAAE gets the highest level for all the harmonics, except harmonic 4. DKOS gets the lowest level for all the harmonics. CHMQ is close to the "average" trumpet. For the "musician" (figure 5), AAAE has a low level for harmonics 1 and 3, CHMQ gets a low level for harmonics 4, and DKOS a high level for harmonics 3.

In conclusions, there is no common point between the configuration (simulations or musician) according to the timbre when we consider sounds in permanent regime: simulations and "musician" produce too different sounds categories and the spectrums are not comparable.

3.2 Series of notes with an increasing dynamics (crescendo)

We consider now sounds with different dynamic. The "musician" sounds are those of Serie2, i.e the 20 repetitions of the same note (Bb4), with a progressive increase of the level of the sound.

For the simulation, we considered the sounds corresponding to an increasing value of the pressure *Pm* (*Pm* = 12, 14, 16, 18, 20, 22 kPa), 4 values of f_L (400; 404; 408; 412Hz) and 3 values of ν_L (-3; -2.5; -2). For each instrument, 42 sounds were generated with these imposed values of *Pm*.

For each sound, we computed 2 descriptors: the spectral centroid and the spectral irregularity. Given that we have variabilities in the descriptors provided by the musician (virtual or real), it is necessary, to compare the results, to fit a model on the data, and then to compare the coefficients of the model. The principle of the modeling is to explain the variance of each descriptor by factors (explanatory variables). For this, we fitted an analysis of variance model (ANOVA) with two factors: the instrument type (*type*, with 3 levels: AAAE, CHMQ, DKOS) and the dynamic of the sounds (*dynamic*, with 6 levels for the simulations: 12, 14, 16, 18, 20, 22 kPa; with 5 levels for the musician: *pp, p, mf, f, ff*). The general equation of the model to explain the descriptor *desc* is given by:

$$\hat{desc} = \mu + \alpha_i . type + \beta_j . dynamic \qquad (7)$$

The estimates of the coefficients α and β of the model are obtained by least square minimization. We fitted one model for each descriptor (*Sc* or *IRR*) and for each configuration (musician and simulation).

For the spectral centroid, the results of the coefficients α of the models are given figure 6 (simulation) and figure 7 (musician).

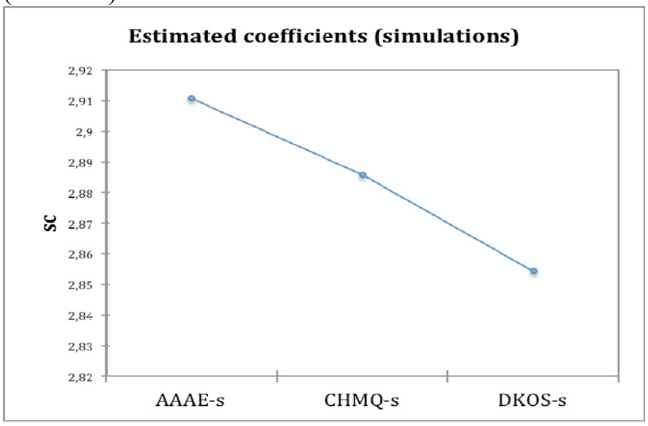

Figure 6: coefficients α of the ANOVA model for the Spectral centroid - simulations

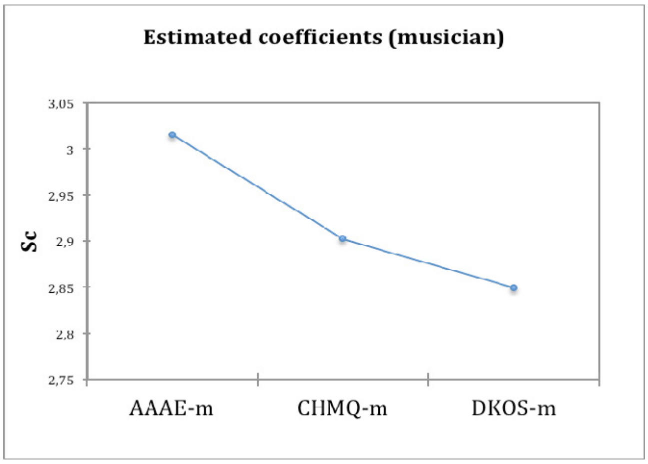

Figure 7: coefficients α of the ANOVA model for the Spectral centroid - musician

We see clearly on figure 6 and 7 that the influences of the trumpets on the spectral centroid are in agreement, for the simulation and the musician: AAAE is in average the "brighter instrument", and DKOS the "less bright". For crescendo sounds, the simulations give results concerning the Spectral centroid which are in agreement with the reality, i.e. with the experiment made with a real musician. This interesting result makes it possible to estimate the brightness of an instrument with simulations, only from a calculation of the input impedance.

The coefficients of the model β (not presented here) show that the amplitude of the coefficient increases with the dynamic of the sound. This result is of course obvious and in accordance with the general behavior of brasses: louder we play, brighter the sound. This confirms the quality of the modeling.

For the spectral irregularity, the results of the coefficients α of the models are given figure 8 (simulation) and figure 9 (musician).

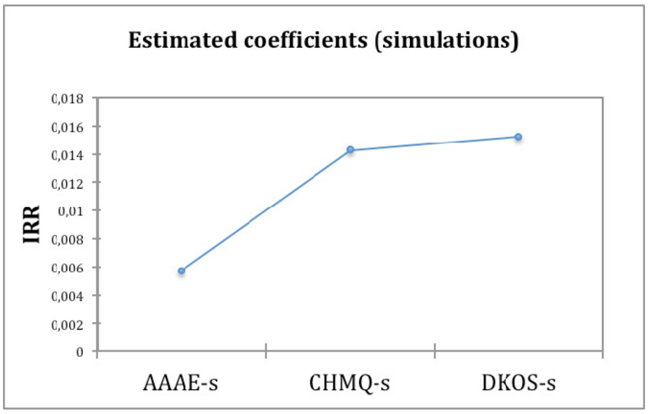

Figure 8: coefficients α of the ANOVA model for the Spectral irregularity - simulations

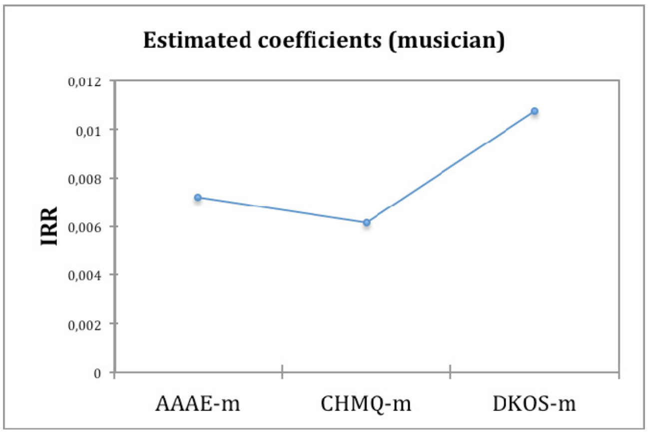

Figure 9: coefficients α of the ANOVA model for the Spectral irregularity - musician

We see on figure 8 and 9 that the influences of the trumpets AAAE and DKOS on the spectral irregularity are in agreement, for the simulation and the musician. The influence of the trumpet CHMQ is different. Further measurements are needed to confirm and to explain the differences.

5 Conclusion

We studied in this paper the similarities and differences between trumpet's sounds simulated by physical modeling or played by a musician. The simulations, based on the harmonic balance technique, used the input impedance of 3 different trumpets as input parameter. Various "virtual musicians" were used to generate a population of sounds.

Concerning the spectrum of the instrument, the simulations and the "musician" produced very different spectrums. We showed that the differences between the trumpets were not comparable, for sounds in permanent regime. For crescendo sounds, we proposed a modeling of descriptors of the sounds with analysis of variance. Two descriptors were modeled: the spectral centroid and the spectral irregularity. We showed that for the spectral centroid, the coefficients of the model were in agreement. This confirms the fact that the simulations by physical modeling are able to transcribe features of the sound of a trumpet sound. The simulations could be used to predict the general brightness of an instrument, from the input impedance. The agreement was not so good concerning the spectral irregularity: further studies are needed to confirm the agreement and to open the door to virtual acoustics for instrument making.

Acknowledgments

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